Soft Frequency Reuse in the Uplink of an OFDMA Network

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***Abstract*—The challenges with deploying a cellular wireless communication network with static frequency reuse in an interference limited environment is that for highly loaded cells, significant regions of coverage will experience high interference levels, resulting in unserviceable low signal-to-interference values. Therefore, interference mitigation approaches as adaptive fractional frequency reuse are considered to tackle the problem. In this paper, different strategies for user and resource allocation are evaluated along with fractional frequency reuse schemes. In contrast to downlink scenarios, we investigate the performance of the OFDMA uplink. It is shown that soft frequency reuse is well-performing in the uplink although it is easy to deploy since it does not rely on resource coordination.**

***Index Terms*—OFDMA, fractional frequency reuse, soft frequency reuse, interference mitigation, simulation**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) is the technology of choice for the coming generation of cellular wireless networks. The WiMAX Forum Mobile System Profile [1] uses the OFDMA physical layer specified in the IEEE 802.16 standard [2]. 3GPP Long Term Evolution (LTE) [3] uses OFDMA on the downlink and Single-Carrier Frequency Division Multiple Access (SC-FDMA) on the uplink. The system model considered in this paper is close to the IEEE 802.16 OFDMA standard but the methodology and the qualitative statements are also valid for SC-FDMA.

Inter-Cell Interference (ICI) mitigation is one of the most crucial design issues for OFDMA networks [4]. A trade-off between system complexity and signaling overhead, total system capacity, and cell edge capacity has to be found. ICI averaging or ICI randomization, ICI avoidance, and ICI coordination are possible approaches for ICI mitigation [5]. The approach in 2G TDMA/FDMA GSM networks was ICI avoidance achieved by a complex frequency planning that ensured an acceptable speech quality at the cell edge [6]. 3G WCDMA networks use a universal frequency reuse and interference randomization is achieved by separating different sectors by scrambling codes.

In upcoming OFDMA networks, the basic radio transmission unit is a resource block representing a number of data subcarriers and OFDM symbols in frequency and time. The allocation of resource block to mobile and power per resource block is done very dynamically on frame basis by the base station which facilitates dynamic and sophisticated ICI mitigation techniques. Two basic approaches are discussed for ICI mitigation in OFDMA networks [5], [7]: The first approach is semi-static or static ICI coordination [5] where every mobile is considered individually and the network nodes coordinate the allocation of resources to users depending on the individual channel conditions of the mobiles. This approach may be assisted by beamforming techniques or multiple user antennas which increases the possibilities for simultaneous resource allocations for users of different sectors. The second approach is Fractional Frequency Reuse (FFR) [7], [8], [9], [10]. In FFR, the users at the cell center utilize the whole frequency band available while the users at the cell edge operate only with a fraction of all sub-channels in order to keep the ICI under a desired threshold. The full load frequency utilization at the center maximizes spectral efficiency while at the cell edge the interference is limited which takes into account the trade-off between cell edge throughput and interference. The key challenges are (1) how to assign mobiles to the center or the edge, (2) how to allocate resources and power to the mobiles, and (3) how to provide a feasible and fair throughput for all users.

Most studies focus on the downlink. However, since interference in the uplink is one of the dominant capacity limiting factors in OFDMA networks, we evaluate different strategies for user and resource allocation for uplink FFR schemes. The main intention of this paper is to investigate the capability of a soft frequency reuse scheme compared to common frequency reuse schemes.

The rest of this paper is organized as follows: In Section II, frequency reuse schemes are described and classified. Afterwards, related work about reuse schemes is summarized. In Section IV, the system model is defined. In Section V, we describe the simulation and evaluation technique. Section VI first defines our evaluation scenarios and then discusses the performance of our scheme in terms of system outage probability. Section VII summarizes key contributions of this paper and provides a brief outlook.

II. Frequency Reuse

Frequency Reuse 3 (FR3) is achieved when the users of one network cell are only allowed to operate on a fraction of the available frequency band. The fraction of the frequency band is allocated in such a way that adjacent cells are operating on different sets of sub-channels. FR3 mitigates inter-cell interference quite effectively due to the large distance between sectors using the same frequency band. However, the resulting higher signal-to-interference plus noise values are achieved on behalf of a loss in resources: only one third can be utilized. With Frequency Reuse 1 (FR1) all resources can be theoretically used since the frequency band is universally reused in every cell in the network. However in practice, high inter-cell interference leads to outage and unfairness at the cell edges. Therefore, FFR schemes constitute a combination of these two schemes, i.e. allow for whole resource utilization at the cell center while interference is mitigated at the cell edge for avoiding outage.

FFR comes in two major variants: Static FFR and adaptive FFR. Static FFR includes pre-planned FR1 or FR3 schemes, or a mixture of them. Commonly, this is achieved with restricting the power of particular frequency resources. Further improvement can be achieved by dynamically adapting the FFR assignments according to the channel quality measurements (CQI) or the path loss of the users. Such adaptive FFR systems can be classified into Partial Frequency Reuse (PFR) [7], [8], [9] and Soft Frequency Reuse (SFR) [9], [10] schemes. PFR provides a separate frequency reuse zone for cell edge and inner cell users. At the cell center FR1 is used and FR3 is used at the cell edge.

In contrast, SFR does not rely on several certain reuse zones. The transmit power of mobiles in particular frequency bands is restricted in such a way that cell edge users of different sectors operate in different frequency bands. Cell center users utilize the whole frequency band. Hence, cell edge users operate in a FR3 zone together with cell center users which do not generate much interference. For trisectorized cell networks, the reserved part for cell edge users is 1/3 of the total band and is chosen orthogonal among neighbor cells. Hence, the reuse scheme factor is 3. Cell center users are allowed to use all frequency bands but with lower priority than the cell edge users. Thus, the effective overall frequency reuse factor is still close to one which guarantees a high spectral efficiency.

III. Related work

Xiang et al. [9] compare different fractional reuse schemes in OFDMA based networks and their parametrization. They study the SFR and PFR in comparison to the FR1 and FR3 scheme in the downlink. They use a static power allocation on the available frequency band. Thus, no adaptive power control was considered. Nevertheless, simulation is done with a sophisticated simulator. As in the present work, they concentrate on Single-Input-Single-Output (SISO) antenna transmissions with fixed antenna patterns. All the results can be seen as basis for a more advanced Multiple-Input-Multiple-Output (MIMO) scenario with adaptive antennas. In [11] the authors simulate a mobile WiMAX system with OFDMA and PFR. They conclude that coverage and throughput increase compared to FR1 and FR3. The work is based on a simulated WiMAX system, but considers only the downlink, a full buffer, and PFR system. Simonsson [12] evaluates reuse schemes in the downlink and uplink of a 3GPP LTE network using a snapshot simulation with a full buffer model. FR1, FR3, PFR, and soft reuse are considered. In the downlink a static transmit power is assumed. Uplink power control is employed and compensates for noise and path-loss. Multiple antenna configurations are tested. The best performing configurations for the reuse schemes are being compared. Link quality, spatial distribution, and service bandwidth impact are discussed. It is concluded that a simple FR1 performs best of the studied reuse schemes. It is further noted that dynamic co-ordination schemes are required to improve the performance for wideband packet data services.

Elayoubi and Haddada [13] create an analytical model for examining the interference and capacity of a 3G LTE uplink scenario. The used SC-FDMA is comparable to OFDMA since both are orthogonal access schemes. They conclude that FFR lies between reuse 1 and reuse 3 in terms of cell outage and achieves a trade-off in fairness and throughput. Fujii and Yoshino [14] also deduce an analytical model for an OFDMA system with FFR. In contrast to Elayoubi and Haddada, they state that FFR increases the system capacity when the system operates under full load. As in our work, OFDMA is applied however the results are based on an analytical model with proportional fair scheduling and PFR.

IV. System Model

For evaluating SFR in the OFDMA uplink a time-invariant system-level Monte Carlo simulation is used. One single transmission frame is simulated with several different spatial user distributions. In doing so, the different approaches how to assign users to frame resources can be investigated in a feasible way. Since this simulation of different allocation strategies is time-independent, time-depended channels as fast-fading channels are not examined in this paper. Especially, the whole scheduling is reduced to resource allocation and power control. Instead, the simulation focus on the interference evaluation due to user distribution, resource allocation, and power control of an OFDMA system. In the following, we define the system model and describe the power and resource allocation in detail.

For an OFDMA wireless network, let the total bandwidth be W. The total number of cells is M. In each cell, the number of users is N, and the number of subchannels is K. Since W is limited, the problem is to allocate resources in an economic way.

A. Power and Resource Allocation

The allocation algorithm decides which mobile is served in the cell and which is blocked due to path loss or interference issues. For each sector $x \in X$, the users are considered according to a resource allocation ordering metric O and either, assigned to the sector home frequency band $\bar{x}$ or, in case of FFR, considered for a foreign band if they are located at the cell center. The cell center users are determined according to a limitation strategy L which restricts users in the foreign band. The common approach is to use a power profile which allows only certain power values for cell center users [9], [10]. Our model is capable of using other strategies to limit the users in the center of a network cell. If it is not possible to allocate a user to a frequency band, the outage selection B is used to block one user, which is not necessarily the user which runs out of resources.

Both, Power Control (PC) and Adaptive Modulation and Coding (AMC) are used. Furthermore, the WiMAX additional optional symbol structure for PUSC is used since it includes reasonable permutation for SFR. If a mobile $n \in N$ has to transmit v bits with modulation and coding scheme (MCS) q, it requires $S_q(v)$ slots. A slot is defined as one subchannel over three OFDM symbols. Now, the power P_q^{Slot} that a mobile n may spend per slot depends on the number of subchannels that the $S_q(v_n)$ slots occupies and that we denote as $K_q(v_n)$. Let P_{max} be the total power that a mobile can spend. Then, the power per subchannel is $P_q^{SubCh}(v_n) = P_{max}/K_q(v_n)$ and the power per subcarrier is $P_q^{SubCa}(v_n) = P_q^{SubCh}(v_n)/18$ since a subchannel occupies 6 tiles or 18 subcarriers in parallel. However, PC adjusts the desired transmit power in order to achieve a target Carrier-to-Interference-and-Noise-Ratio (CINR) that is sufficient to guarantee the desired frame error rate (FER) [15]. CINR is the SINR of a modulated signal. The target CINR is MCS specific and denoted as γ_q^*. Now, if I is the average interference per subcarrier at the receiver, L is the propagation loss between transmitter and receiver, and N_0 is the per subcarrier thermal noise power, then the target power is $P_q^*(I, L) = L + \gamma_q^* + 10\log_{10}(N_0 + I) + \zeta$, where ζ is an offset for power control imperfection or user mobility. The used MCS q_n^* of a mobile n is the MCS consuming the least resources while requiring less than P_q^{Slot} power. That means if I_x^A is the average per subcarrier interference for sector x on frequency A and $L_{n,x}$ is the path loss from mobile n to sector x, then $q_n^* = \max_q \left[P_q^*(I_x^A, L_{n,x}) \leq P_q^{Slot}\right]$.

B. Resource Allocation Metrics

The whole resource allocation is split into several parts. The limitation strategy defines the cell center. Further on, the user allocation metric defines the order the users are considered. Third, the outage selection blocks users if necessary. In case of the limitation strategy, they even determine the frequency reuse scheme. We consider the following approaches which are evaluated in Section VI in detail.

1) User Allocation Metric: The user allocation metric O defines in which order the users are assigned to a slot in the frame. *Random order* O_{Random} is the most simple method.

Another order is called *PropGain*. PropGain uses the propagation gain $L_{n,\bar{x}}$ to the sector $\bar{x}$ of a mobile n as allocation metric

$$O_{PropGain} = L_{n,\bar{x}}. \tag{1}$$

The mobile with highest propagation loss is scheduled first since it requires more resources than a mobile next to the base station. Additionally to PropGain, *PropGainRatio* also considers the path loss to other sectors. The path loss $L_{n,\bar{x}}$ of a mobile n belonging to sector $\bar{x}$ divided by the path loss to other sectors $\sum_{x_i, x_i \neq \bar{x}} L_{n,x_i}$ is derived for all frequency bands. The minimum ratio of all frequency bands

$$O_{PropGainRatio} = \min_i \left[\sum_{x_i, x_i \neq \bar{x}} \frac{L_{n,\bar{x}}}{L_{n,x_i}}\right] \tag{2}$$

defines the priority of a mobile.

It is also possible to consider the interference for the allocation order metric. *IntfSum* is defined as the minimum of all frequency bands of the following term. The average power to other sectors $E[P_{q,i}^*]$ that transmit at frequency band i as user q is weighted by the path loss L_{n,x_i} to these sectors,

$$O_{IntfSum} = \min_i \left[\sum_{x_i, x_i \neq \bar{x}} \frac{E[P_{q,i}^*]}{L_{n,x_i}}\right]. \tag{3}$$

2) Limitation Strategy: A limitation strategy L is defined to control the number of users in the inner band. If there is no inner band at all (limitation strategy L_{Zero}), the cell uses a FR3 scheme. Otherwise, if the inner band is not limited, all mobiles are able to use the whole frequency band. Thus, this limitation strategy, called $L_{Unlimited}$, is equal to FR1.

To generate a feasible reuse 1 zone, two metrics are evaluated in this paper. First, $L_{AggregatePower}$ allows a group of users to transmit in the FR1 zone if their aggregated transmit power is lower than a threshold. Second,

$L_{PowerLimitation}$ works the other way round and individually limits the power of the FR1 users which results in a low interference of these users. This is equal to the power profile proposed in [9] for downlink.

3) Outage Selection: After allocation metric and FFR reuse limitation strategy, outage selection B decides which users are blocked if the resources are not sufficient for all mobiles.

B_{Random} ensures fairness. The users are blocked randomly. $B_{OutageMin}$ considers the resource consumption which at the end leads to outage minimization. The users are blocked according to their propagation gain.

Finally, $B_{WeightedRandom}$ provides a mixture of both which achieves a trade-off between fairness and performance. The users are weighted according to the path loss relative to the path loss of all users in the sector.

V. System-Level Simulation Methodology

The system level simulations of the OFDMA uplink were carried out using a time-invariant WiMAX Monte Carlo simulator. It is based on fundamentals of the IEEE 802.16m Evaluation Methodology Document [15]. One transmission frame is simulated with a fixed traffic demand of all users. This means that every user constantly tries to send v bits and the simulation calculates a feasible solution according to the power and resource allocation algorithms.

The cell simulation case is based on a 5x5 deployment with hexagonal 3-sector sites. In order to avoid bounding effects and thus, an overestimation of the system performance, wrap around is applied which ensures that all cells experience the same interference characteristics. Table I provides central modeling parameters and assumptions. The simulator is able to process non-MIMO antenna configurations including different downtilts, diverse antenna patterns, and different user traffic volumes. In all simulations, error free feedback from the MS to the BS is assumed. PHY OFDMA mode is designed for frequency bands below 11 GHz. For the simulations, frequencies in the 3.5 GHz band are chosen. We consider an OFDMA system with FFT size of 512 subcarriers. After eliminating the guard subcarriers, we effectively use 432 data subcarriers.

TABLE I
SIMULATION PARAMETERS

Cellular layout	25 hexagonal, trisectorized cells
Site-to-site distance	0.5 km
BS/UE antenna height	30 m, 1.5 m
Carrier frequency, Bandwidth	3.5 GHz, 5 MHz
FFT size, # subchannels	512, 24
Frame length	5 ms
Subchannel mode	Additional optional symbol structure for PUSC
Antenna configuration	Single-Input-Single-Output
Antenna horizontal pattern	$A(\theta) = -min\left[12 \cdot (\frac{\theta}{\theta_{3dB}})^2, A_M\right]$, $\theta_3 dB = 70°, A_m = 20dB$
Antenna vertical pattern	$A(\delta) = -min\left[12 \cdot (\frac{\delta-\delta_{tilt}}{\delta_{3dB}})^2, A_M\right]$, $\delta_3 dB = 11°, A_m = 18dB$
BS/UE antenna gain	14 dBi/0 dBi
Path loss model	$PL[dB] = 35.2 + 35\log_{10}(d) + 26\log_{10}(f/2)$
UE thermal noise density	-174 dBm/Hz
UE maximal power	200 mW
Channel State Information	Perfect CSI

VI. NUMERICAL RESULTS

The focus of this paper is to investigate the capability of SFR in the uplink of an OFDMA network according to different user distributions and different resource allocation algorithms. To provide a feasible evaluation, SFR is compared with other frequency reuse schemes. The trade-off between an interference minimal FR3 scenario and a frequency efficient FR1 scenario is investigated. Especially, the interaction of mobiles and the emitted interference of mobiles is considered carefully. The performance of the frequency reuse schemes is affected by the resource allocation. Consequently, the allocation algorithms are compared at the beginning.

A. Scenario

For the system evaluation, several parameters are used which are enumerated for completeness. Mainly, the results are generated with 1 to 26 users per sector. The users transmit 1024 bits per frame. Previously, the optimal vertical downtilt of the base station antenna was determined. It is set in all simulations to 11 degree. The downtilt is highly dependent on the cell size. If not properly configured, the cell is either not fully covered or the base station causes interference to other sectors. In this paper, we consider the average cell outage percentage as performance measure. It is calculated per cell sector and afterwards, the mean is derived of all 75 sectors to get the average outage. The outage percentage is equivalent to the throughput in the sector due to a fixed transmission rate of the mobiles. Every plotted curve of the results shows the mean value of at least 20 samples. Additionally, the 95 % confidence intervals are drawn to ensure the reliability of the stochastic results.

B. Simulation results

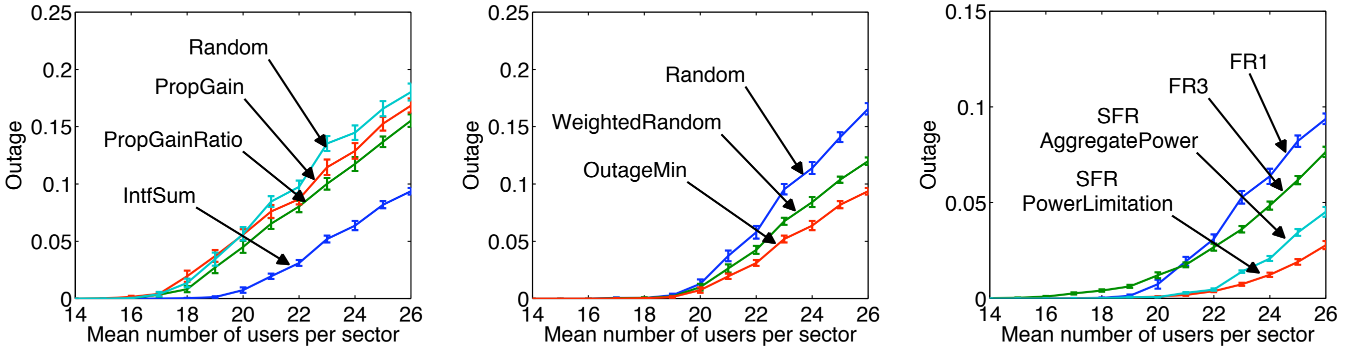
The performance of the frequency reuse schemes depends on the resource allocation. Consequently, first the allocation algorithms are compared in a FR1 scenario. The main intention of the resource allocation is to efficiently utilize the transmission resources. In Fig. 1(a) the four strategies implemented in the simulator are compared. The figure shows the total outage at the y-axis. The x-axis displays the mean number of users per sector. The simple random metric which selects an arbitrary user performs worst. In contrast, the metric which considers the interference to other sectors is significantly better than all other metrics. This leads to the fact that interference consideration is important. As expected, a mobile should be allocated first if it has a high propagation loss and a high interference from other sectors since it requires the most power to transmit the data. If only the propagation loss is considered as with the PropGain or PropGainRatio metric, some users are assigned to a slot although another user would generate less interference on this slot. Similar to the different resource allocation algorithms, several outage selection strategies are also possible. Fig. 1(b) shows the effect of different outage selection strategies. The axes are kept to outage percentage and average users per sector. The allocation metric is set to IntfSum. Remarkable is the performance of the OutageMin strategy. At an outage of 5 % it supports on average one additional user per cell sector or 3 users more per cell compared to the Random strategy. However, the Random strategy should be considered if the fairness plays a major role. The OutageMin strategy is used in the following only.

For the evaluation of the frequency reuse schemes we begin with FR1 compared in contrast to FR3. FR1 is presented with the best performing allocation strategy IntfSum. Elayoubi and Haddada [13] state with an analytical model that reuse 1 performs significantly better than reuse 3. However, they do not include interference interaction of mobiles. They only average the interference of all mobiles and the sector. Fig. 1(c) includes the total outage percentage of FR1 and FR3. For less than 21 users per sector the FR1 scheme performs better than FR3. But, in a loaded scenario with more than 22 users per sector the interference is increasing and FR3 turns out to be the better strategy.

SFR with individual power limitation is depicted in Fig. 1(c). Compared to Elayoubi and Haddada [13] and Fujii and Yoshino [14] in our case the SFR performs significantly better since the frequency utilization is better than FR3. Users in the inner sector are allowed to use a foreign band and thus, the sector is able to serve more users than in the reuse 3 case. At an outage of 5 % it performs at about 16 % or 4 users per sector on average better than the other schemes. Consequently, we recommend the SFR with PowerLimitation strategy as a frequency efficient and well performing reuse scheme in the uplink.

Besides SFR with PowerLimitation strategy which limits individually the power of a mobile, we also evaluated the AggregatePower limitation strategy. The SFR with this limitation strategy also performs better than FR3 but worse than SFR with PowerLimitation strategy.

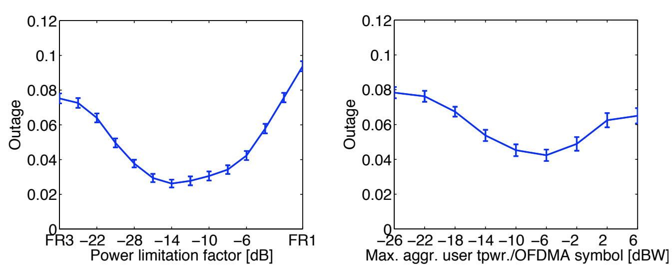
The input parameters of the SFR strategies are further investigated. PowerLimitation restricts the maximum power of a mobile if it wants to send on a foreign band in the inner zone. Consequently, the mobiles which require few power and thus, are located next to the antenna are candidates for this reuse 1 zone in the SFR scenario. A parameter study is performed in the following to determine the optimal value. If the parameter is set too low, no mobile is able to transmit in the reuse 1 zone.



(a) FR1 outage with different allocation metrics (b) FR1 with different outage selection strategies (c) SFR with two different limitation strategies in comparison with FR1 and FR3 frequency scheme

Fig. 1. Allocation metric parameter study and comparison of the frequency reuse schemes

The mobiles cannot use the reuse 1 zone. Thus, the scenario degenerates to a reuse 3 scenario. If the parameter is set too high, every user can transmit as regular. Hence, the scenario degenerates to a reuse 1 scenario. Simulations are done for 25 users per sector to determine the optimal PowerLimitation parameter. The results are shown in Fig. 2(a). The x-axis shows the values of the parameter. The y-axis displays the outage with this parameter. The minimum is at -14 dB which results in an optimal PowerLimitation parameter. The factor should be adapted along with the increasing number of users. With more users, the power limit has to be decreased to keep the interference low. For the AggregatePower limitation strategy the same is done and is shown in Fig. 2(b). The tuning parameter for SFR AggregatePower is the maximum aggregated transmit power per OFDMA symbol. The threshold was determined to -6 dBW for the users in the reuse 1 zone.



(a) SFR PowerLimitation parameter plot (b) SFR with AggregatePower limitation

Fig. 2. SFR parameter optimization

VII. Conclusion

In this paper, the soft frequency reuse is investigated along with frequency reuse 1 and frequency reuse 3 schemes. Several resource allocation and outage strategies are evaluated for the uplink of a wireless mobile OFDMA network. Work is done with a WiMAX simulator.

The results show that for a medium number of users frequency reuse 1 can decrease the average outage in a network compared to reuse 3. This is also stated with an analytical model by Elayoubi and Haddada [13]. However, for loaded cells the inter-cell interference influences the cell performance and frequency reuse 3 performs better. Fractional frequency reuse schemes provide a combination of reuse 1 and frequency reuse 3. Therefore, soft frequency reuse is evaluated which is considered for next generation wireless mobile networks. At an outage of 5 % it performs at about 16 % or 4 users per sector better than the reuse 3 scheme. Since soft frequency reuse is easy to deploy and does not rely on resource coordination, it is a good consideration for wireless OFDMA networks. Consequently, soft frequency reuse is further investigated. A parameter study is presented to determine the optimal algorithm parameter.

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